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SEARCH FOR COLD GAS IN CLUSTERS WITH AND WITHOUT COOLING FLOWS

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ABSTRACT. The dominant galaxy in each of ~ 40 clusters has been studied using co-added *IRAS* survey data, and 11 of these galaxies have been observed for CO ($J=1 \rightarrow 0$) emission with the NRAO 12 m telescope at Kitt Peak. Half of the galaxies in our sample are in clusters reported to have cooling flows while the other half are not. Six of the galaxies appear to have been detected by *IRAS* at fairly low flux levels, in addition to one previously known strong detection; all seven have reported cooling flows. No detectable CO emission (to 2-3 mK) was found in any of the 11 galaxies observed. Assuming accretion rates of $\sim 100 M_{\odot} \text{ yr}^{-1}$, the star formation rates and efficiencies in these galaxies must be quite high in order to render the CO undetectable. At the same time, the infrared luminosities of these galaxies is unremarkable, suggesting that the correlation between star formation efficiency and infrared luminosity found for spirals may not hold for cooling flows.

INTRODUCTION. In the last fifteen years, X-ray observations of clusters of galaxies have led to the discovery that the hot intracluster gas in the cores of many clusters appears to be cooling on timescales short in comparison with the ages of the clusters. If not reheated, the gas will flow toward the cluster center where it may be accreted by the central dominant galaxy. Estimates of the mass-flow rates range over $5-500 M_{\odot} \text{ yr}^{-1}$ (cf. Sarazin 1986). Debate over the possible role of reheating (Bertschinger and Meiksin 1986; Silk *et al.* 1986), however, has cast some doubts on the existence of flowing – as opposed to simply cooling – gas in these clusters.

An important question related to the existence of cooling flows is the ultimate fate of the accreted material. The most obvious and generally assumed repository is stars. Since the gas must first pass through a cold, neutral phase, a fundamental test for the accumulation of cooling intracluster gas in cluster cores is the search for the cold gas that must feed the star formation. The *IRAS* and CO observations we present here are directed at detecting such a reservoir.

OBSERVATIONS. We co-added *IRAS* survey data about the central dominant galaxy in each of ~ 40 clusters, and observed a subset of 11 galaxies with the NRAO 12 m telescope at Kitt Peak for CO ($J=1 \rightarrow 0$) emission. Our goal was to search for cold interstellar gas in these galaxies, with a focus on the possible contribution from accretion of the cooling intracluster gas. Our sample was drawn from the list of Stewart *et al.* (1984) of X-ray clusters; about half the clusters in their list show evidence for cooling flows (cooling times less than H_0^{-1}) while the other half do not. Additional cooling-flow clusters were taken from Sarazin (1986; and references therein) and Romanishin and Hintzen (1988).

RESULTS. Seven of the galaxies appear to have been detected by *IRAS*, although except for NGC 1275 (which is already in the *IRAS Point Source Catalog*), none can be classified as unquestionable detections. On the basis of signal strength, positional coincidence of the $60\mu\text{m}$ and $100\mu\text{m}$ sources, and proximity to the optical image of the galaxy, we ranked six sources as follows: A 1126 and A 2199, very probable detections; A 2063, A 576, and A 400,

likely detections; and A 1983, marginal detection. For these seven galaxies, the infrared luminosities range from $0.83 \times 10^{10} L_\odot$ (A 400) to $13 \times 10^{10} L_\odot$ (A 426); 3σ upper limits for the remaining galaxies range from $0.33 \times 10^{10} L_\odot$ to $22 \times 10^{10} L_\odot$. The median value of L_{IR} (detections and upper limits) is roughly $4.5 \times 10^{10} L_\odot$. (We have used $H_0 = 50 \text{ km s}^{-1} \text{ Mpc}^{-1}$ for all distant-dependent quantities.)

No CO was detected in any of the sources observed. (The data for NGC 1275 were lost due to a previously undiscovered software error in the telescope system; this galaxy has subsequently been detected in CO by Lazareff *et al.* [1989]). Upper limits to the total mass of molecular gas in each galaxy have been determined on the basis of the assumed proportionality of integrated CO line intensity and H_2 column density, where the conversion of Sanders *et al.* (1986) has been used. Our values are consistent with the observational results of Bregman and Hogg (1988) for the dominant galaxies in A 1126, A 2199, and 2A 035+096.

The CO luminosity upper limits are plotted against the IR luminosities (detections and upper limits) as open circles (\circ) in Figure 1. For comparison, the empirical L_{IR} - L_{CO} relation derived by Young *et al.* (1986), in three ranges of dust temperature, for spiral galaxies is also shown (dashed lines). The results for spirals are explained quite plausibly in terms of a correlation between molecular gas content and star formation. Evidently, the CO luminosities (and presumably the molecular gas masses) of the galaxies we observed would in many cases have to be substantially lower than our upper limits, in order for these galaxies to follow the same general trend found for spirals. If star formation is proceeding in these galaxies in a manner similar to that in spirals, then it is either doing so at fairly low rates, or not producing massive stars, or both. Any of these possibilities must be reconciled with the continuous influx of star-forming material if a cooling flow is believed to be present.

Also shown in Figure 1 are five galaxies which were either detected by *IRAS* but not observed in CO (\square -symbol), or observed in CO but no *IRAS* data were obtained (\times -symbol). The L_{IR} - L_{CO} relation of Young *et al.* has been used in these cases to predict the luminosity in the unobserved waveband based on the luminosity in the observed waveband. The predicted luminosities may provide sensitivity limits for future observations.

DISCUSSION. We use a simple formalism to estimate the amount of cold interstellar gas that we might expect from a cooling flow at the present time, t . Assuming $dU/dt =$ growth rate of the ISM, $dS/dt = \eta U/\tau =$ star formation rate, and $\dot{M} =$ mass-flow rate = constant, where η is the star formation efficiency, τ is the lifetime of the ISM against star formation and all masses are in units of M_\odot , then $dU/dt = -\eta U/\tau + \dot{M}$. Because both η and τ may vary with time, we use $\langle \eta/\tau \rangle = t^{-1} \int_0^t [\eta(t')/\tau(t')] dt'$, which allows the simplification

$$U(t) \approx U_0 \exp(-\langle \frac{\eta}{\tau} \rangle t) + \dot{M} \langle \frac{\eta}{\tau} \rangle^{-1} \approx \dot{M} \langle \frac{\eta}{\tau} \rangle^{-1}.$$

We therefore expect the size of the reservoir to scale with \dot{M} , τ , and inversely with the star formation efficiency η .

Figure 2 shows mass-flow rates taken from the literature, plotted against our derived ISM masses or mass upper limits (IR-determined masses were derived following Jura [1986]). There does not appear to be any correlation. (Note that both the derived \dot{M} and M scale with distance-squared.) Taken at face value, this lack of correlation seems to add to the doubts about the existence of cooling flows. Alternatively, the failure to detect CO and IR

LUMINOSITY COMPARISON

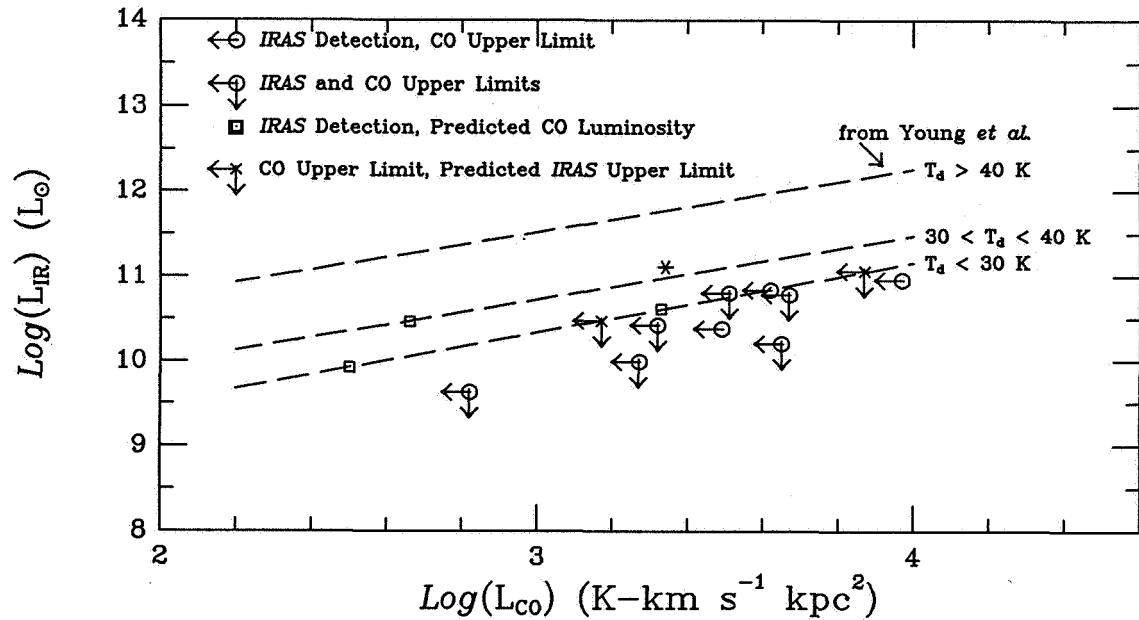


Figure 1. Luminosity comparison. The logarithms of L_{CO} and L_{IR} are plotted against each other. The symbols indicate whether only CO data (\times), only IRAS data (\square), or both (\circ) were obtained. The dashed lines show the $L_{\text{CO}}-L_{\text{IR}}$ relation determined by Young *et al.* (1986) for spirals; this was used to predict L_{IR} for \times 's and L_{CO} for \square 's. All upper limits are 3σ . The asterisk (*) is NGC 1275; L_{CO} is from Lazareff *et al.* (1989), scaled to $H_0 = 50 \text{ km s}^{-1} \text{Mpc}^{-1}$.

MASS vs FLOW RATE

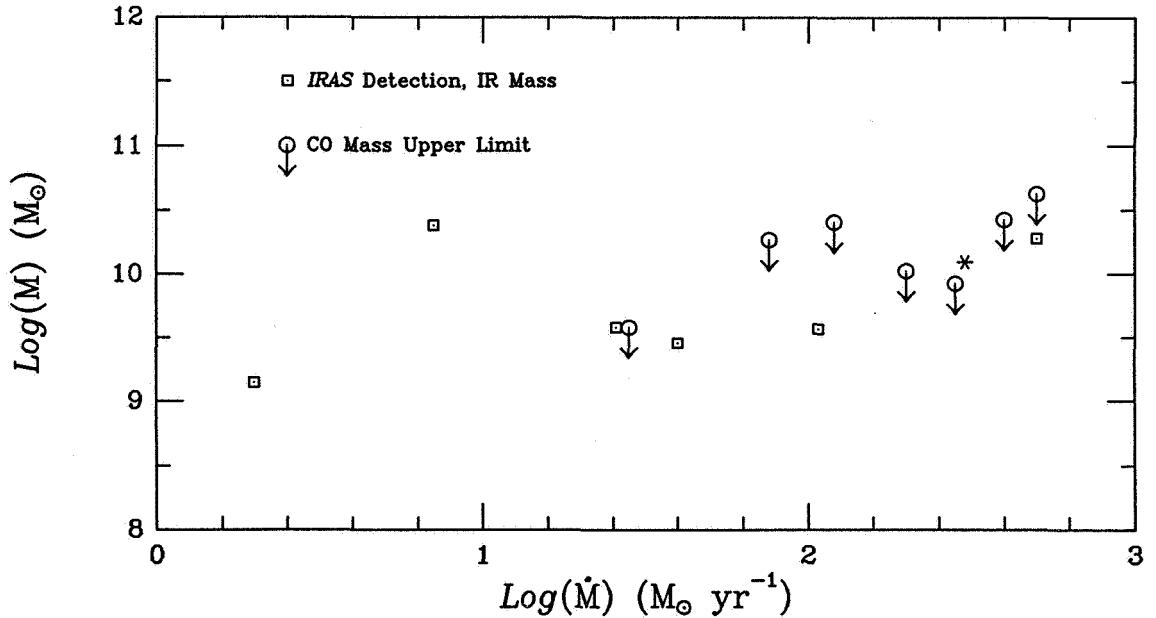


Figure 2. Mass vs flow rate. The logarithms of the mass-flow rates taken from the literature plotted against the logarithms of the IR-derived masses (\blacksquare) or 3σ CO mass upper limits (\circ). The asterisk (*) is NGC 1275; M_{CO} is from Lazareff *et al.* (1989), scaled to $H_0 = 50 \text{ km s}^{-1} \text{Mpc}^{-1}$.

emission from most of the galaxies in our sample could indicate that the star formation rates and efficiencies are high, and the reservoir of star-forming gas is therefore relatively small. This possibility can be evaluated by deriving $\langle \eta/\tau \rangle^{-1}$ based on the assumed existence of cooling flows.

We redefine the quantity $\langle \eta/\tau \rangle^{-1}$ as $\tau_{SF} = 2M/\dot{M}$, where the factor of 2 is assumed to account roughly for the fraction of the cold ISM detected: only half in the form of H_2 in the case where M is derived from the CO upper limits; or only half the neutral gas being warm enough to be detected by *IRAS* at $100\mu\text{m}$ (cf. Jura 1986) in the case where M is derived from the *IRAS* data. For most of the clusters with reported cooling flows, we find $\tau_{SF} \sim 10^8$ yr, fairly short considering that this is a global value.

In spiral galaxies, high star formation efficiencies have been associated with high dust temperatures, high infrared luminosities, and large ratios of $L_{\text{IR}}/L_{\text{CO}}$ (Young *et al.* 1986). Our results suggest that if cooling flows exist, then star formation fed by them is highly efficient. At the same time, however, the IR luminosities of the galaxies we observed are relatively low, a property which in spirals seems to indicate fairly low star formation rates. If the formation of massive stars is somehow suppressed in cooling flows, vigorous low-mass star formation might still proceed without significantly heating the interstellar gas and dust. This would be consistent with cooling flow models in which star formation is characterized by a truncated initial mass function (e.g., Sarazin and O'Connell 1983). Of course, if cooling flows are not actually present, or if mass-flow rates have been greatly overestimated, then the relatively small ISM masses and low infrared luminosities we find would be consistent with the results for spirals, without invoking different modes of star formation.

An additional question that can be addressed with our data, not directly related to cooling flows, is whether the FIR properties of cD galaxies differ from elliptical galaxies. To do this, we compared our results for cluster-dominant galaxies with those of Jura *et al.* (1987) for ellipticals. Using their findings for $F_{\nu}(B)$ versus $F_{\nu}(12\mu\text{m})$, the lack of detections in our sample at $12\mu\text{m}$ is consistent with cDs being scaled-up ellipticals. Similarly, the ISM masses we derived from the $100\mu\text{m}$ fluxes, a factor of ~ 100 greater than those found for ellipticals, are consistent with the typical mass estimates for cDs and ellipticals (cf. Sarazin 1986). Evidently, cD galaxies appear to be "oversized" ellipticals with regard to their FIR properties.

SUMMARY. Our results are summarized as follows:

1. About 40 clusters with and without cooling flows have been searched for IR emission with *IRAS* co-adds; 11 of these have also been observed for CO emission.
2. Six new *IRAS* detections have been discovered; no CO detections were made.
3. If cooling flows exist, star formation rates and efficiencies must be high in order to render the CO undetectable; yet at the same time IR luminosities are observed to be relatively low.
4. cD galaxies look like scaled-up ellipticals with regard to their FIR properties.

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